$\bar{\nu}_\mu CC\pi^0$ in NOvA:

Status of Muon Antineutrino Charged-Current Neutral Pion Production Differential Cross Section Measurement in the NOvA Near Detector

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on behalf of the NOvA Collaboration

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NOvA Experiment

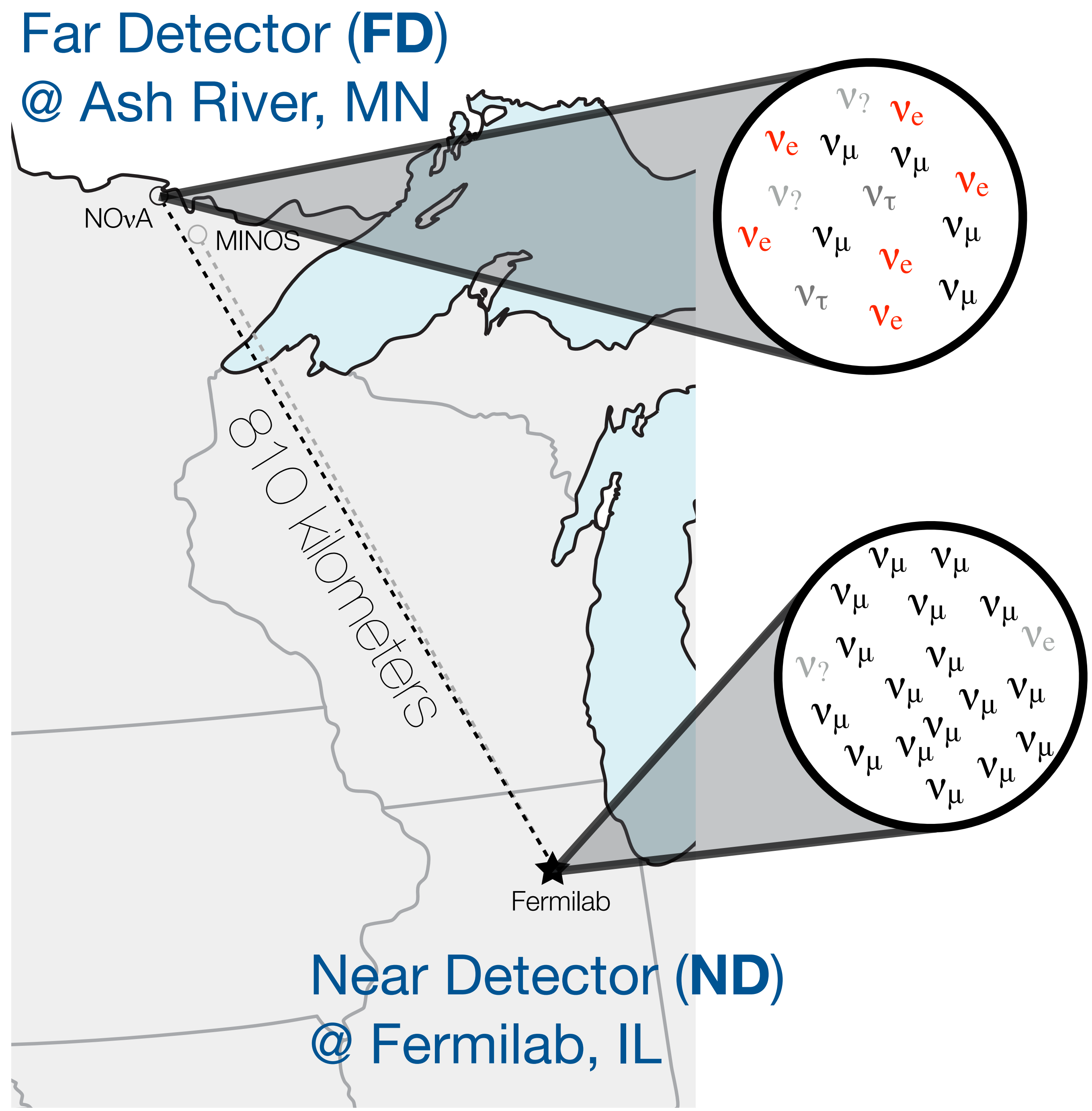
- NOvA is a long-baseline neutrino oscillation experiment

- NuMI beam at Fermilab
  — Neutrino mode (ν_μ) and antineutrino mode ($\bar{\nu}_\mu$)

- Two functionally-identical tracking calorimeter detectors
  — Liquid scintillator
  — Off-axis by 14.6 mrad
  — Separated by ~810 km

- Measure oscillations through 4 channels:

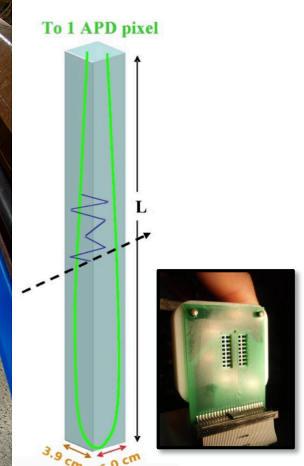
$$\nu_\mu \to \nu_\mu\,, \nu_\mu \to \nu_e\,, \bar{\nu}_\mu \to \bar{\nu}_\mu\,, \bar{\nu}_\mu \to \bar{\nu}_e$$

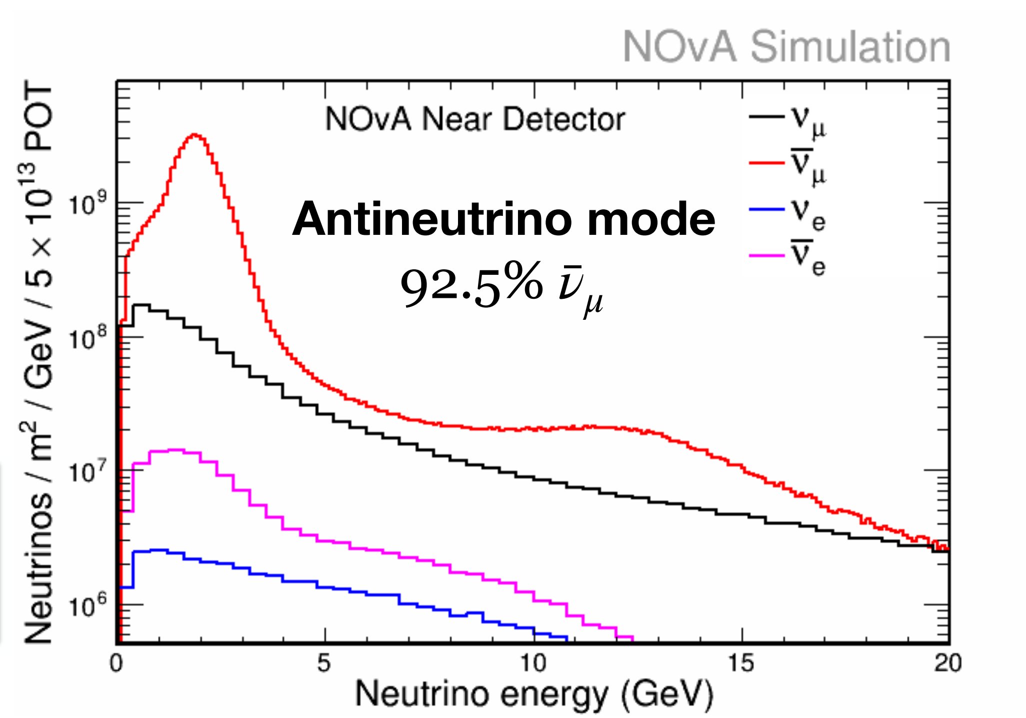


$\bar{\nu}_\mu CC\pi^0$ @ NOvA near detector (ND)

- NOvA near detector (ND):
  - — Tracking calorimeter made of PVC cells filled with liquid scintillator oil and a loop of wavelength-shifting fiber connected to avalanche photo-diode (APD).
  - — Narrow band neutrino beam 1-3 GeV peaks at ~2 GeV.
  - — High flux purity (92.5% $\bar{\nu}_\mu$) and huge statistics (~1 million $\bar{\nu}_\mu$CC interactions) in antineutrino mode.

C	Cl	H	O	Ti
65.9%	16.1%	10.7%	3.0%	2.4%



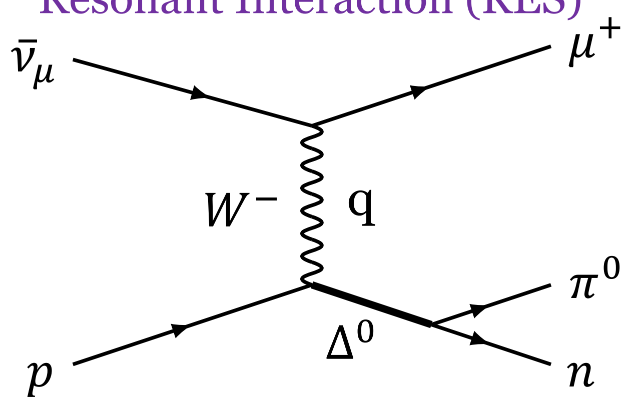


- **Goal** of this measurement:
  Measure charged-current differential cross section with respect to π^0 momentum and angle in the NOvA near detector with muon **antineutrino** beam.

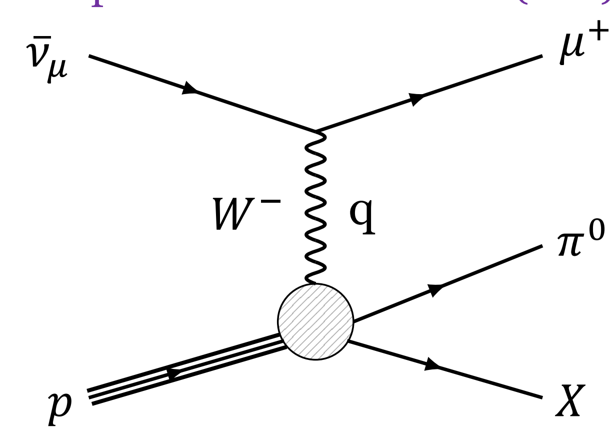
Motivation

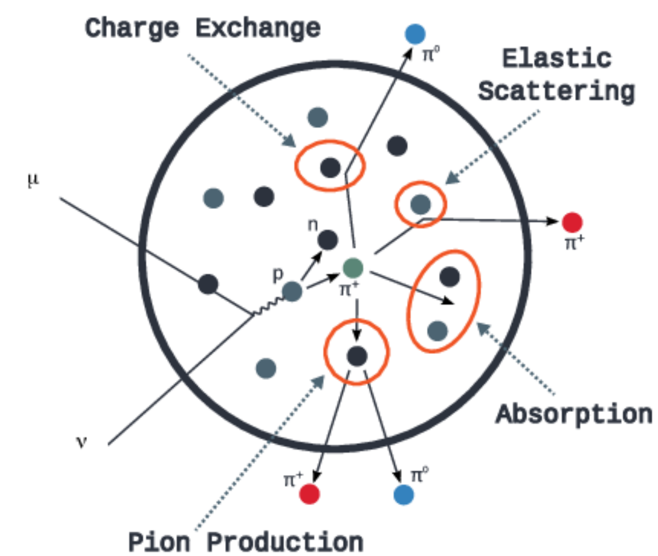
- Neutrino oscillations are measured as function of neutrino energy and accurate estimation of E_ν requires knowledge of final states.
- $\bar{\nu}_\mu \mathrm{CC}\pi^0$ provides insight on background to $\nu_e/\bar{\nu}_e$ appearance.
- Knowledge of $\bar{\nu}_\mu \mathrm{CC}\pi^0$ production constrains systematic uncertainties for neutrino interaction models.

Resonant Interaction (RES)



Deep Inelastic Interaction (DIS)

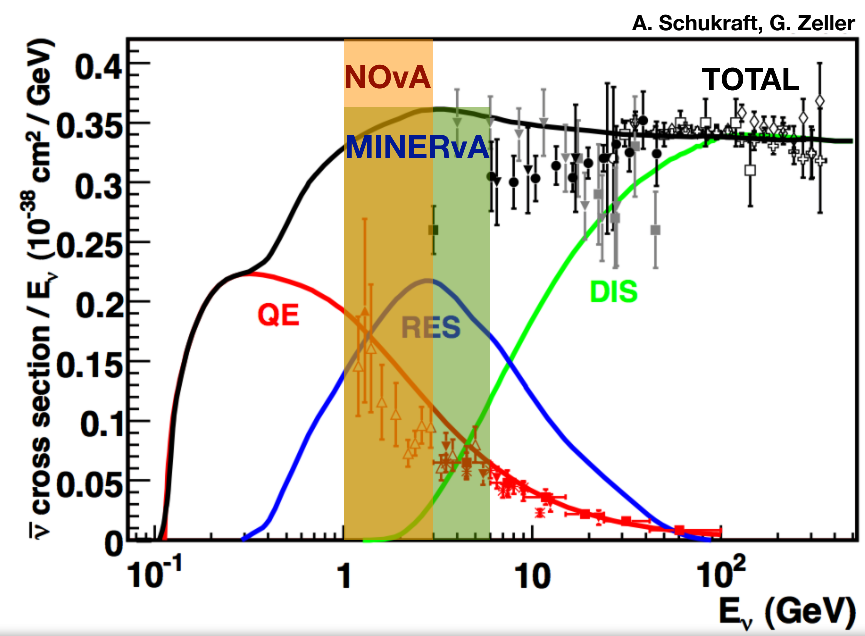




- One previous measurement on charged-current π^0 production used antineutrino beam — MINERvA (Phys. Lett. B 749, 130-136 (2015)).

$\bar{\nu}_\mu$ mode

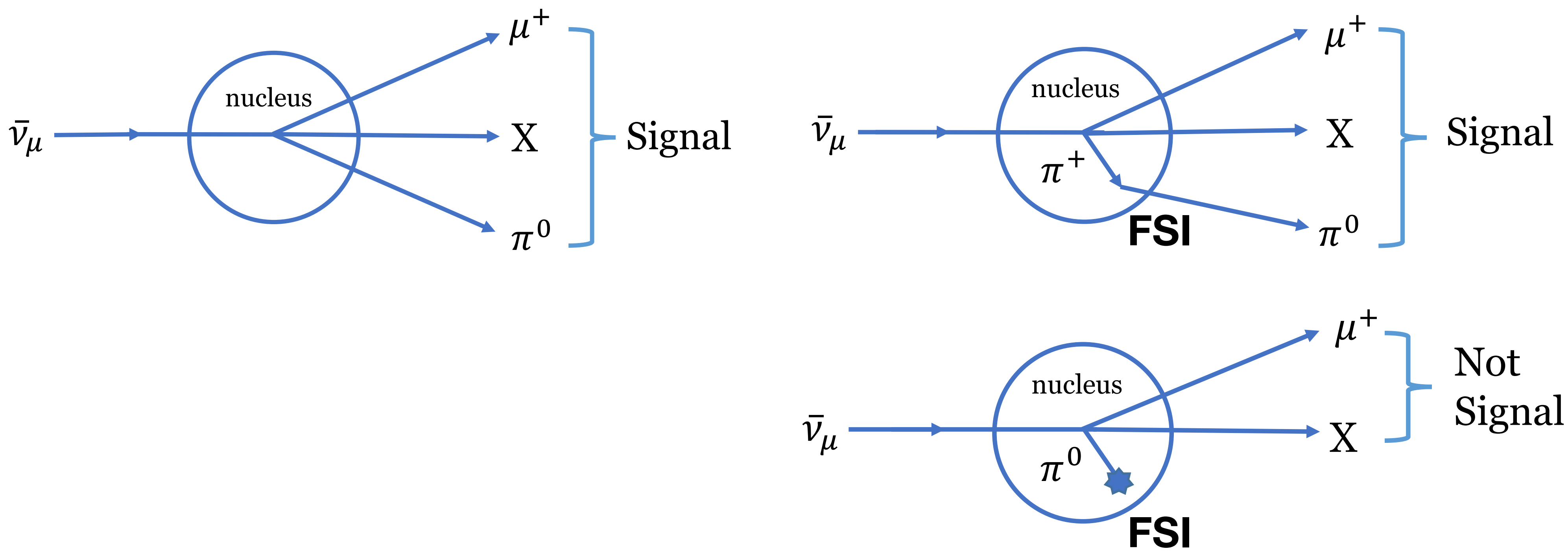
NOvA compared to MINERvA
~ 6x POT
~ 10x selected signal



Signal Definition

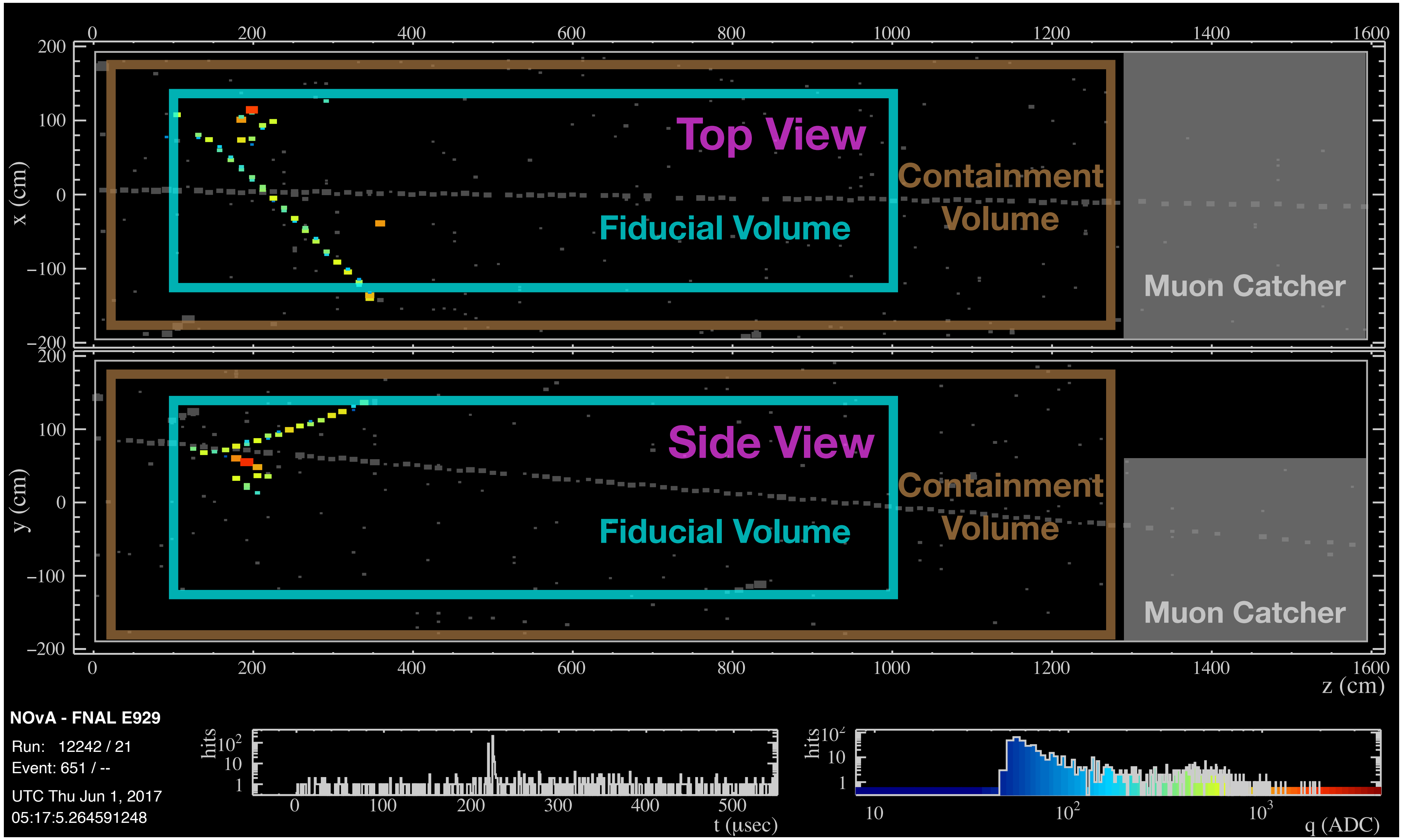
$$\bar{\nu}_{\mu} + N \rightarrow \mu^{+} + \pi^{0} + X$$

1. $\bar{\nu}_{\mu}$CC interaction in fiducial volume
2. At least one π^0 in the final state produced at the vertex
   — including π^0 produced in final state interactions (FSI) within the target nucleus.



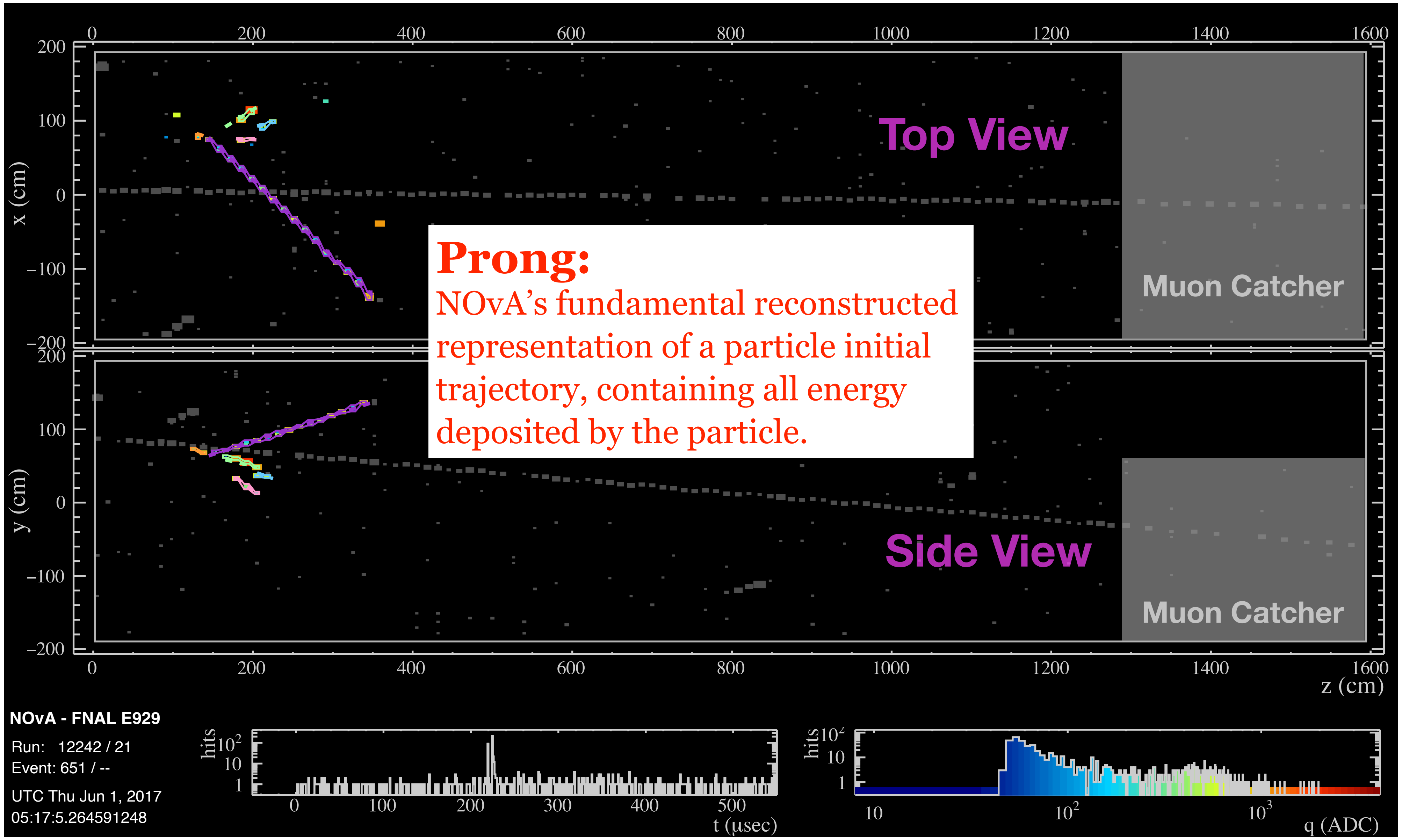
Secondary π^0: π^0 produced outside the target nucleus is **background**.
— Particle decay or inelastic scattering during particle propagation

Sample Selected Signal Event



1. Reconstructed interaction vertex is inside the fiducial volume.
2. Tracks/Showers are contained.
3. $\bar{\nu}_\mu$CC interaction — A long muon track.
4. π^0 in the final state — Two distinct electromagnetic showers ($\pi_0 \to \gamma + \gamma$).

Sample Selected Signal Event



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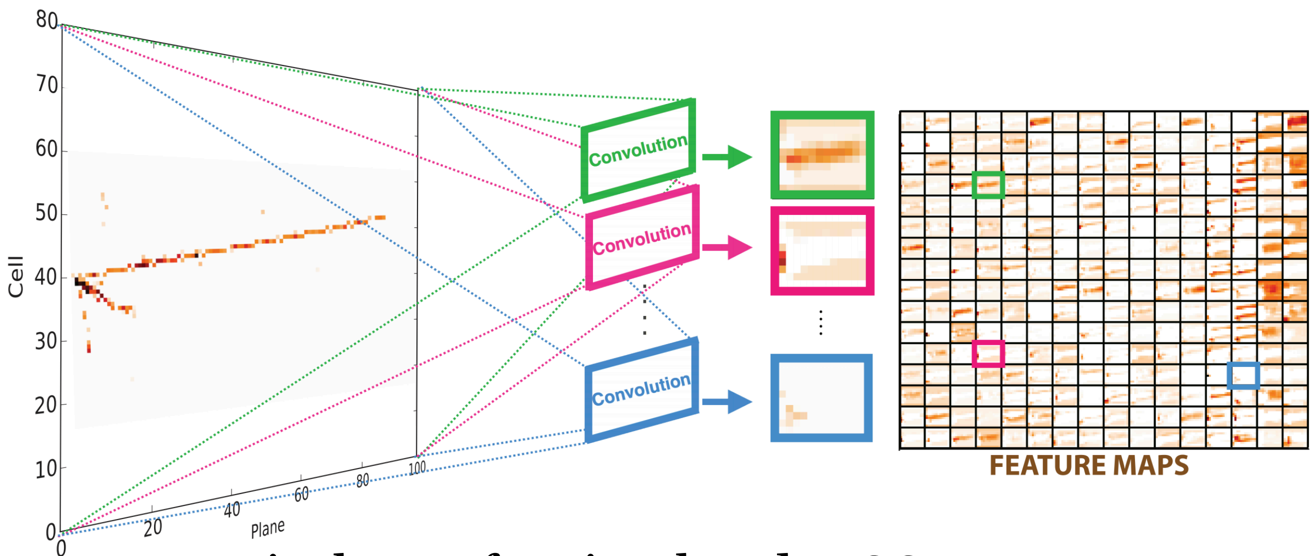
NOvA Event/Particle Identification

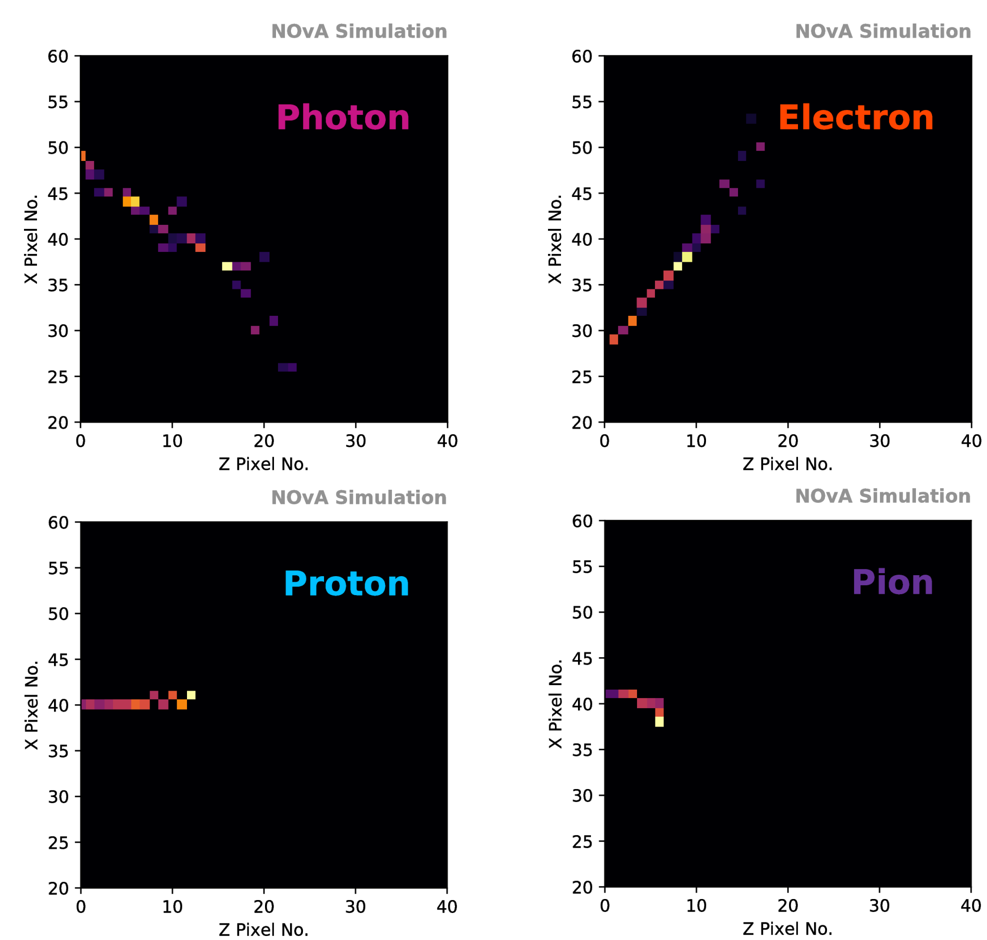
- Event and particle identification is done using a **Convolutional Neural Network** (CNN) in NOvA.
  - — Convolutions are applied to **pixel maps** of the events and particles, which are trained to identify particular features (tracks vertex, showers, etc).



Pixel map for simulated ν_μCC event.

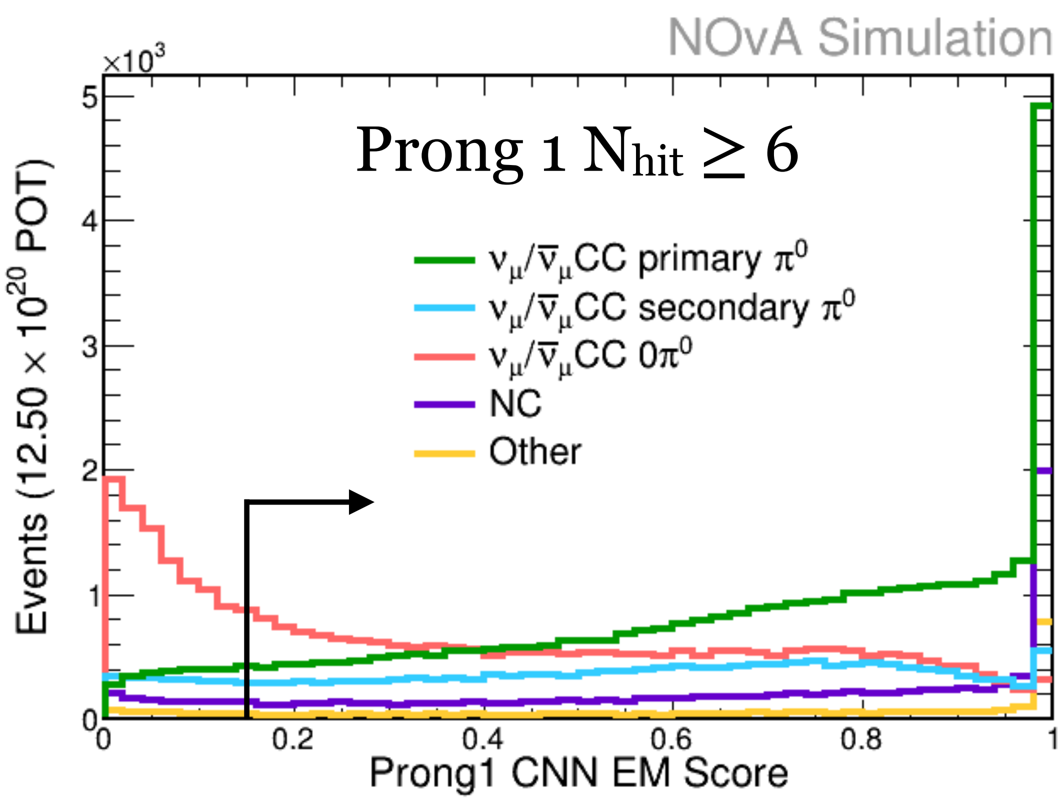
- Single particle simulation sample was chosen for training.
  - — $e, \gamma, \pi^{\pm}, p, \mu$
  - — Uniform in momentum, angle, generated position.

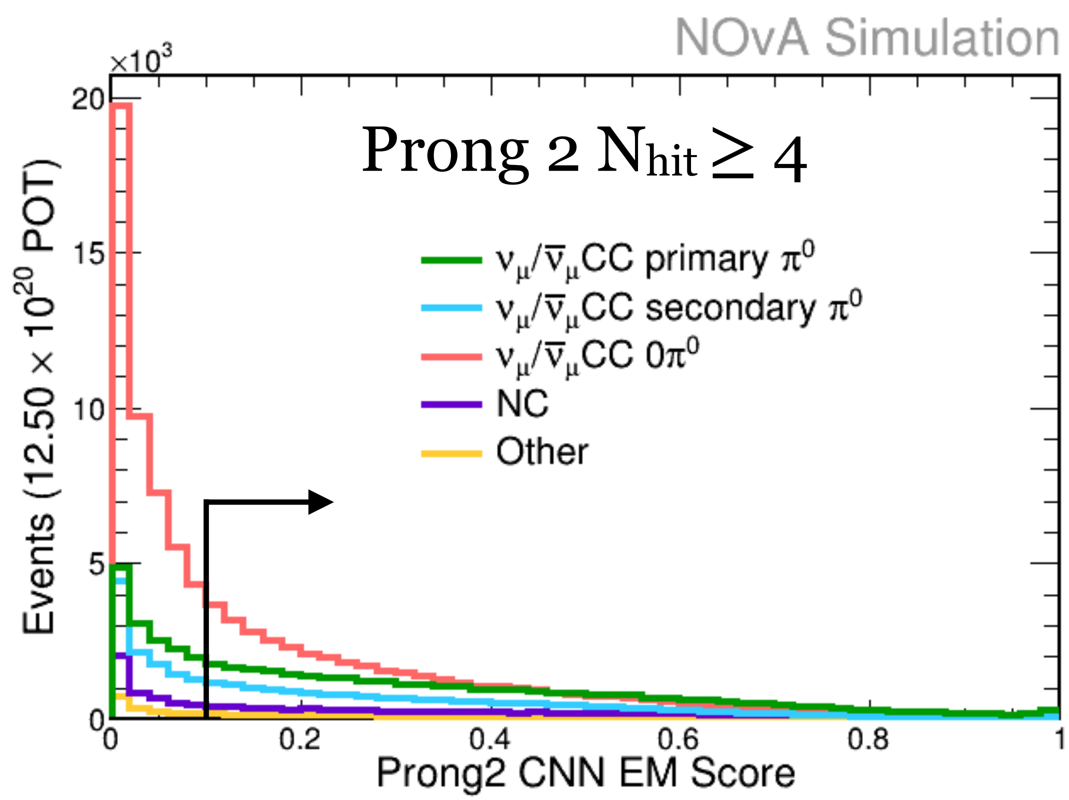
- **Binary classification** for prongs: EM-like vs. non-EM-like
  - — Equal fraction of EM sample and non-EM sample $(\gamma + e)$ vs. $(p + \pi^{\pm})$



Sample Selection

- **Prong 1 & 2**: Two candidate EM-like prongs in $\bar{\nu}_\mu$CC preselection sample
  - — Identify muon-like prong
  - — Select two candidate EM-like prongs with highest CNN EM scores (Prong 1 CNN EM score > Prong 2 CNN EM score)
  - — Background reduction cut (muon kinetic energy cut) and prong quality cuts applied



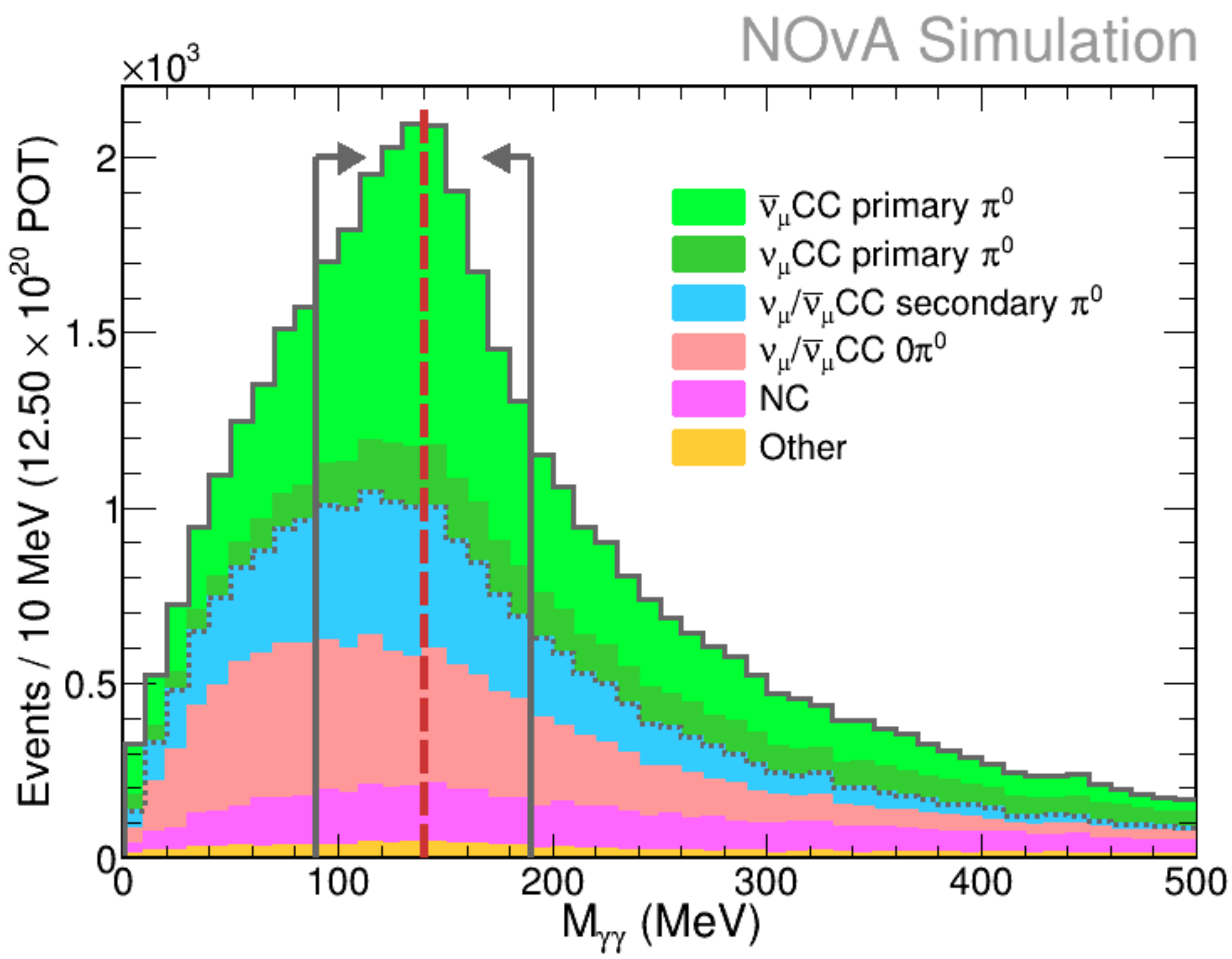


π^0 Selection

- Prong CNN EM score cut
  - — Prong 1 CNN EM score > 0.15
  - — Prong 2 CNN EM score > 0.10

Invariant Mass Distribution

$$m_{\gamma\gamma} = \sqrt{2E_{\gamma_1}E_{\gamma_2}(1 - \cos\theta_{\gamma\gamma})}$$



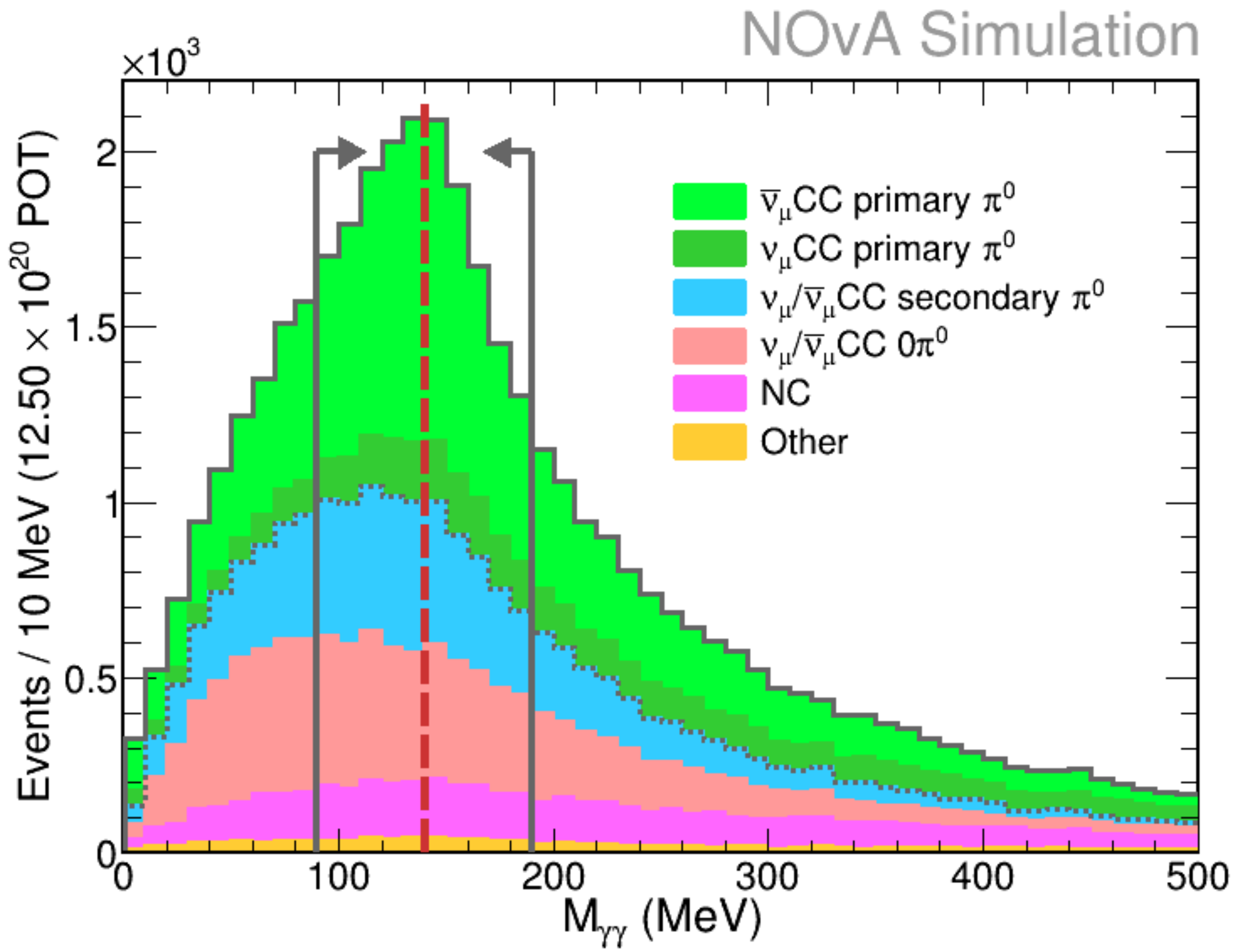
- Signal
  - — $\bar{\nu}_\mu/\nu_\mu$CC with primary π^0
- CCπ^0 Background
  - — $\bar{\nu}_\mu/\nu_\mu$CC with secondary π^0
- Non-CC or Non-π^0 Background
  - — $\bar{\nu}_\mu/\nu_\mu$CC without π^0
  - — NC
  - — Other

- Invariant mass peak cut — [90, 190] MeV

All Simulated Signal	Selected Events	Selected Signal	Efficiency	Purity
1.564e6	18008	8736	0.56%	48.5%

Invariant Mass Distribution

$$m_{\gamma\gamma} = \sqrt{2E_{\gamma_1}E_{\gamma_2}(1 - \cos\theta_{\gamma\gamma})}$$



- Signal
  - — $\bar{\nu}_\mu/\nu_\mu$CC with primary π^0
- CCπ^0 Background
  - — $\bar{\nu}_\mu/\nu_\mu$CC with secondary π^0
- Non-CC or Non-π^0 Background
  - — $\bar{\nu}_\mu/\nu_\mu$CC without π^0
  - — NC
  - — Other

Template fit!

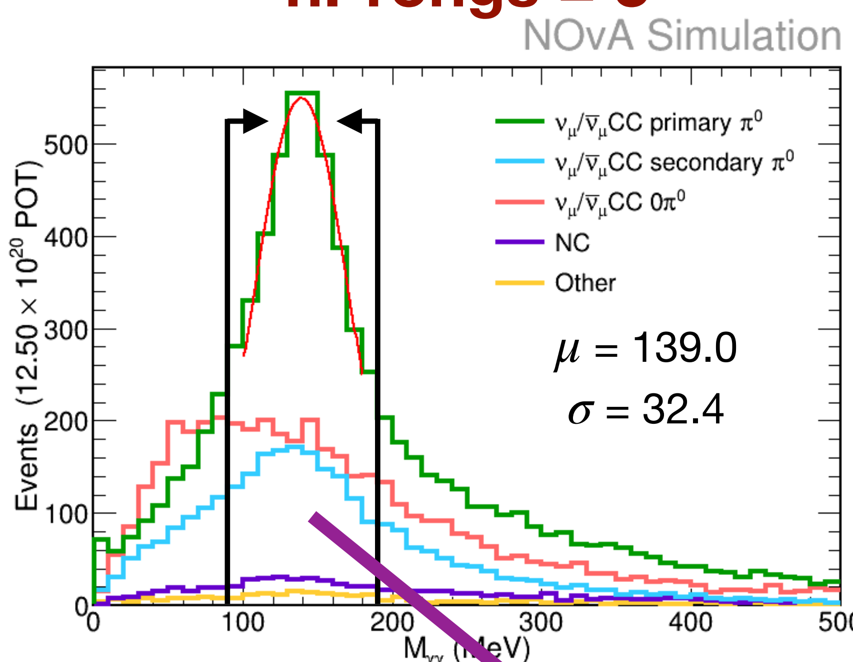
- Invariant mass peak cut — [90, 190] MeV

All Simulated Signal	Selected Events	Selected Signal	Efficiency	Purity
1.564e6	18008	8736	0.56%	48.5%

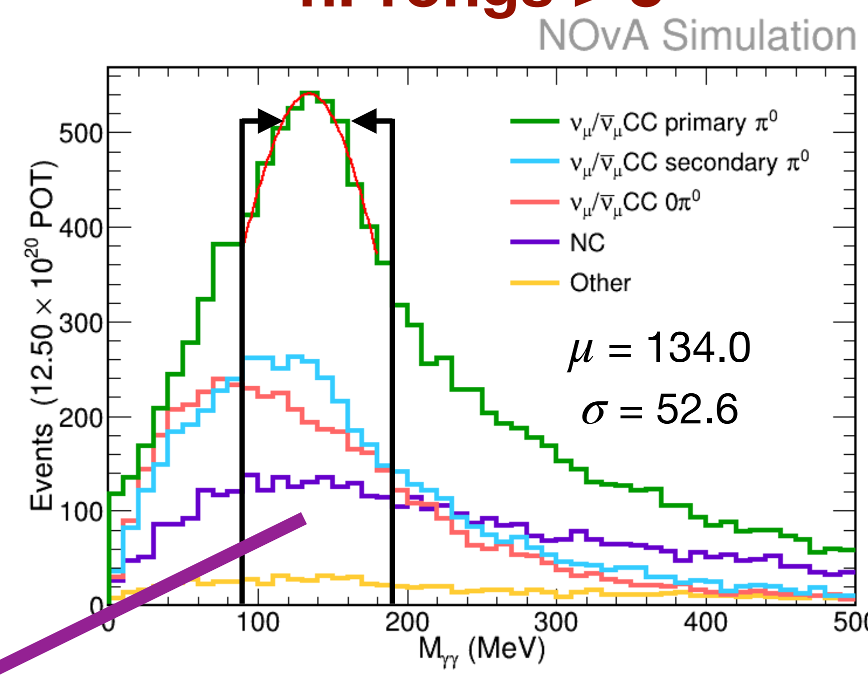
Number of Prongs Cut

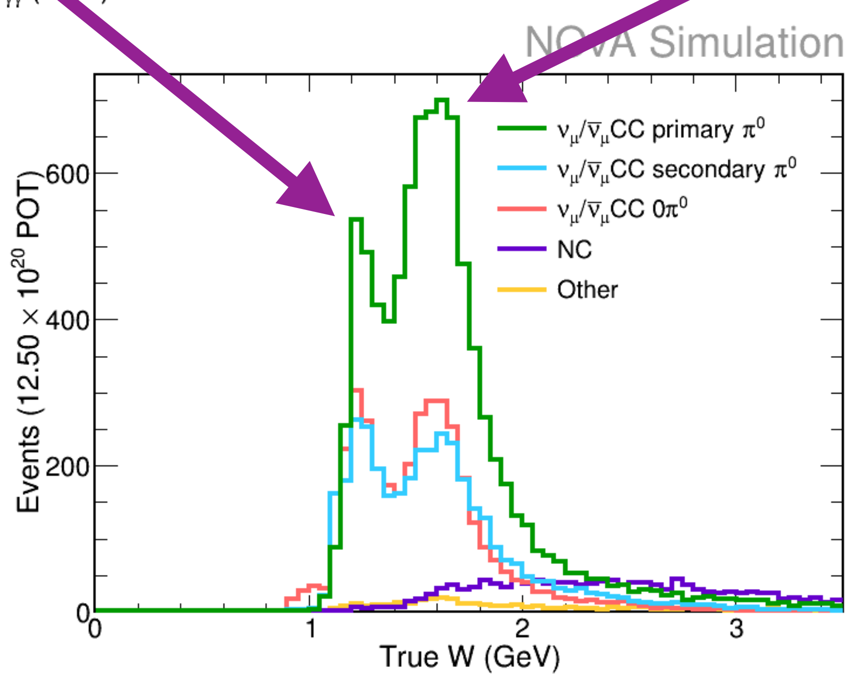
- Number of prongs cut splits selected sample into two orthogonal samples:
  — nProngs = 3 & nProngs > 3, corresponding to two average W values
- Make measurements in two W bins

nProngs = 3



nProngs > 3





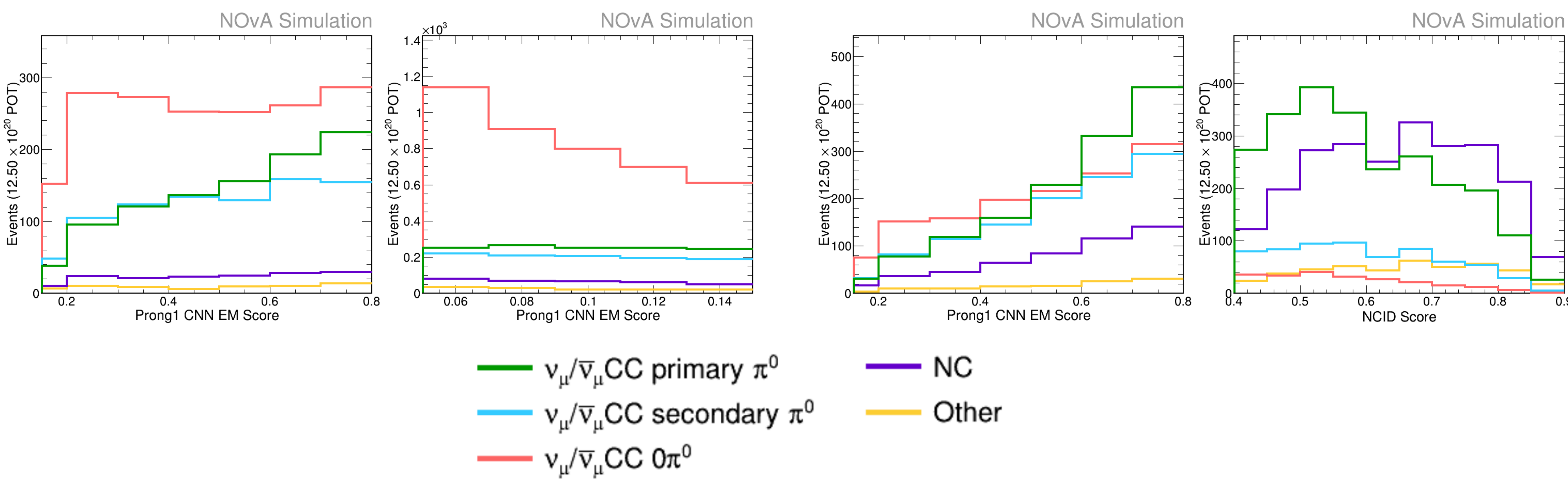
	Signal Sample Size	Purity
nProng = 3	46%	53.1%
nProng > 3	54%	45.2%

Background Estimation

Data-driven **template fit**: Estimate $\bar{\nu}_\mu/\nu_\mu$**CC** $\mathbf{0\pi^0}$ and **NC** backgrounds.

- **4 sidebands:**
  nProngs = 3: $\bar{\nu}_\mu/\nu_\mu$CC $0\pi^0$-1 sideband, $\bar{\nu}_\mu/\nu_\mu$CC $0\pi^0$-2 sideband
  nProngs > 3: $\bar{\nu}_\mu/\nu_\mu$CC $0\pi^0$-1 sideband, NC sideband
- **Templates:**
  — $\bar{\nu}_\mu/\nu_\mu$CC $0\pi^0$ sidebands template: Prong1 EM CNN Score
  — NC sideband template: A Boosted Decision Tree (BDT) trained score (NCID)

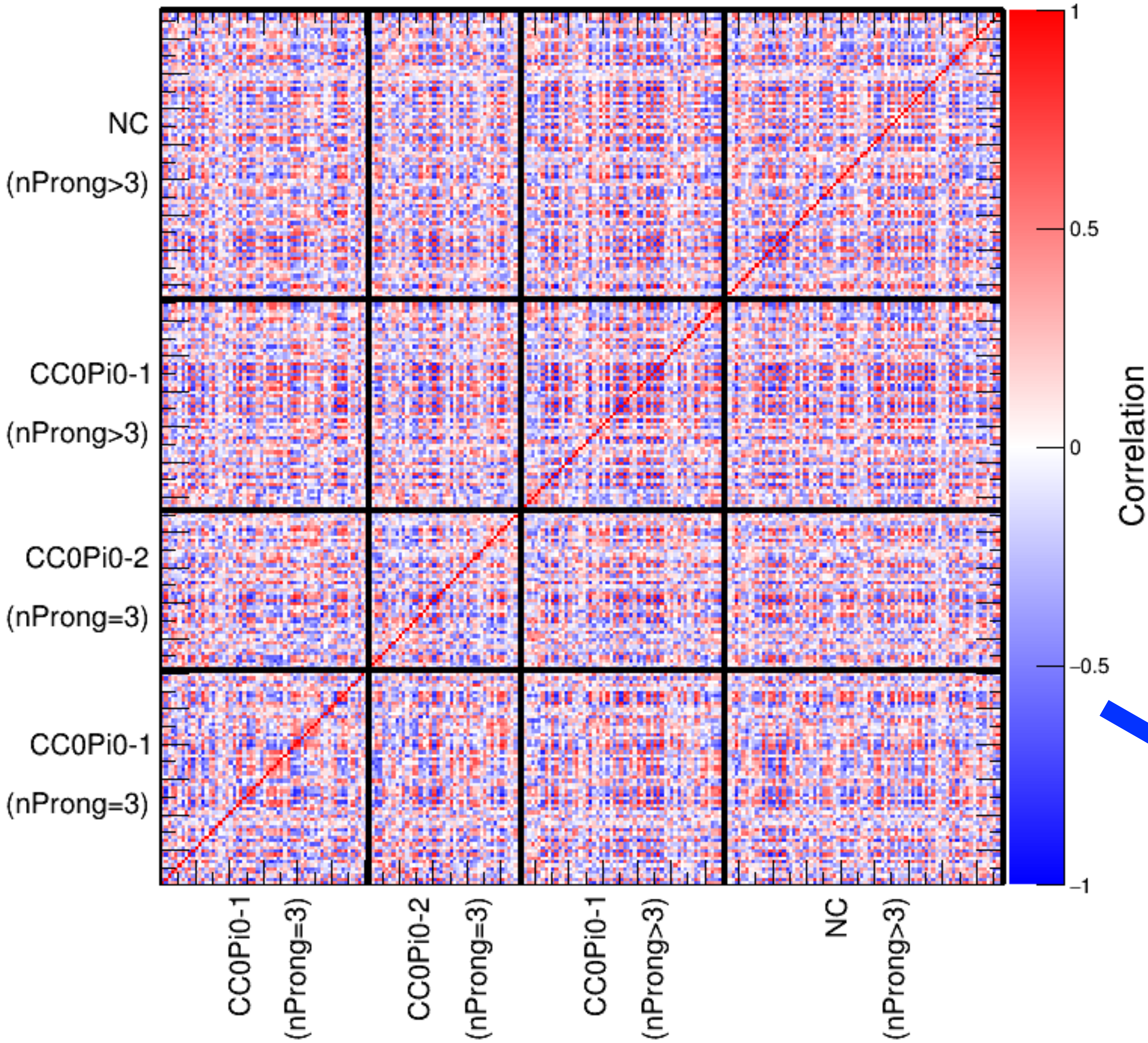
nProngs = 3 sample sidebands **nProngs > 3 sample sidebands**



Background Estimation

Data-driven **template fit**: Estimate $\bar{\nu}_\mu/\nu_\mu$CC $\boldsymbol{0\pi^0}$ and **NC** backgrounds.

- Project each kinematic bin down to the template distributions broken down by signal and background components across all sidebands.
- Construct covariance matrix V, where $V = V_{stat} + V_{syst}$



- Globally fit template normalization parameters by minimizing

$$\chi^2 = (x-\mu)^T V^{-1} (x-\mu)$$

correlation matrix

"normalized" covariance matrix

Fake Data Fit Results

nProngs = 3

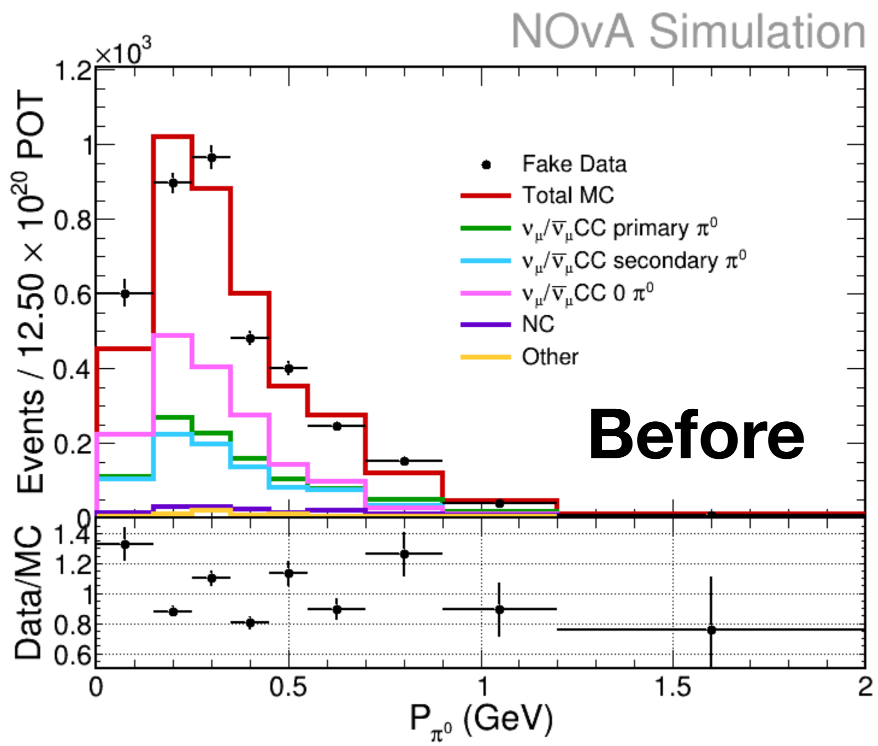
Fake Data:

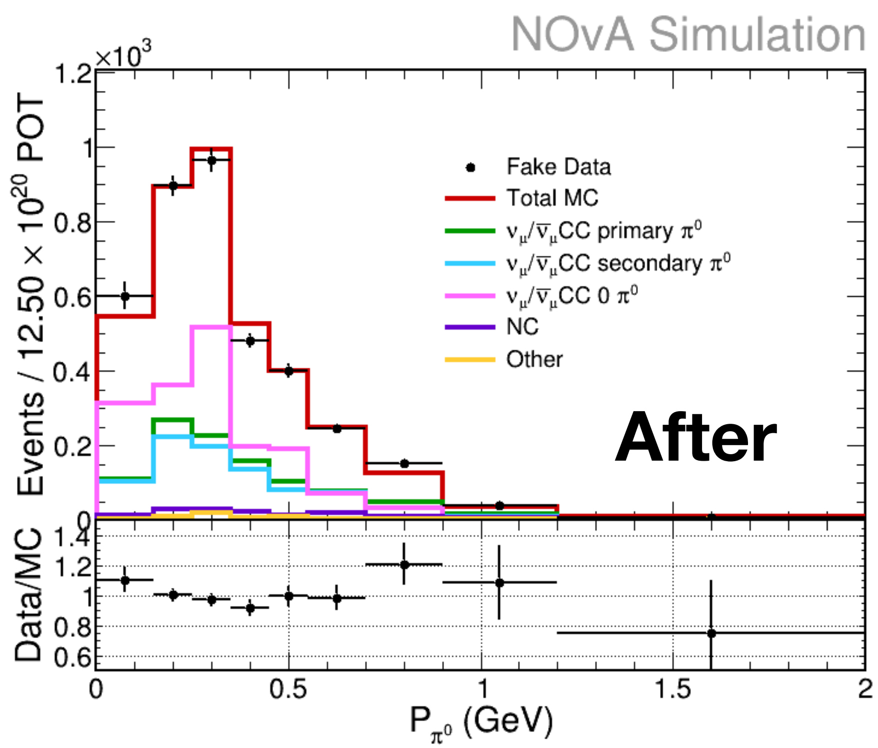
Adjust $\bar{\nu}_\mu/\nu_\mu$CC $0\pi^0$ normalizations up or down by 20% in alternating bins

Fitting χ^2:

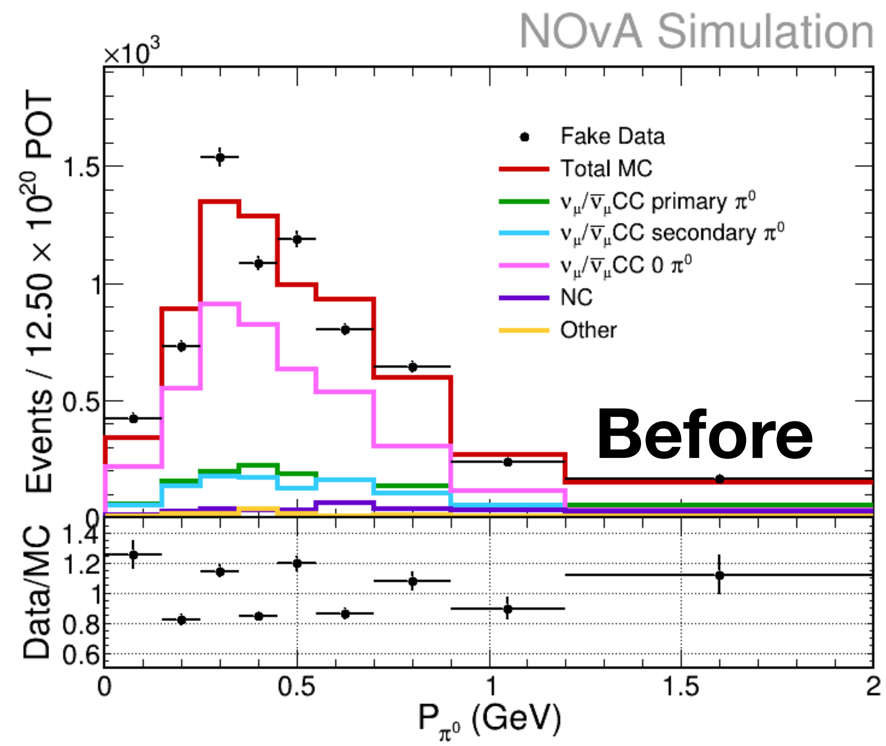
525 (Before)→260 (After)

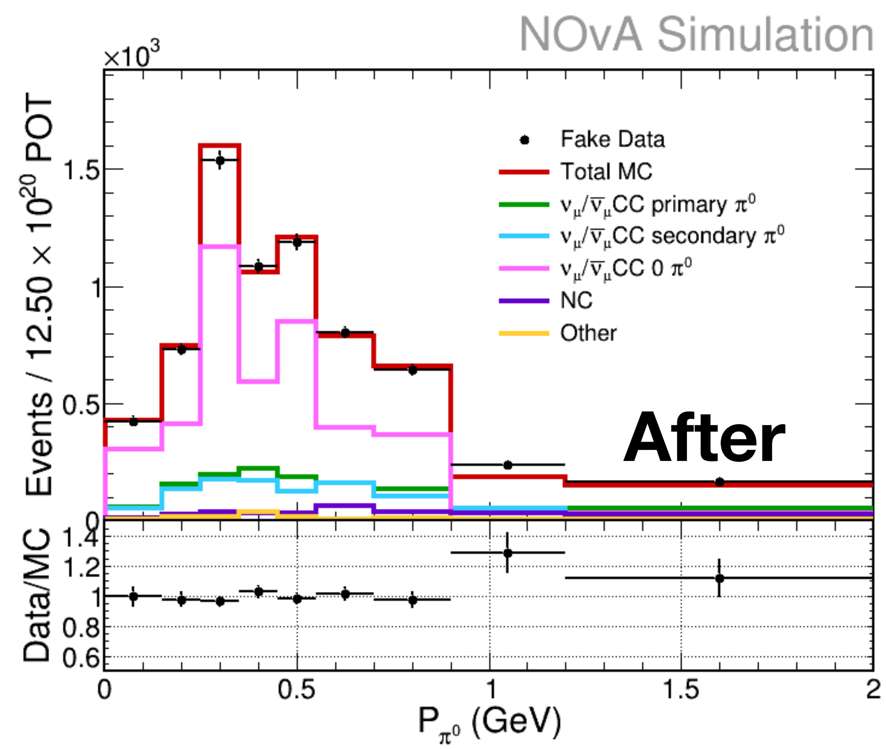
$\bar{\nu}_\mu/\nu_\mu$CC $0\pi^0$ - 1 Sideband





$\bar{\nu}_\mu/\nu_\mu$CC $0\pi^0$ - 2 Sideband





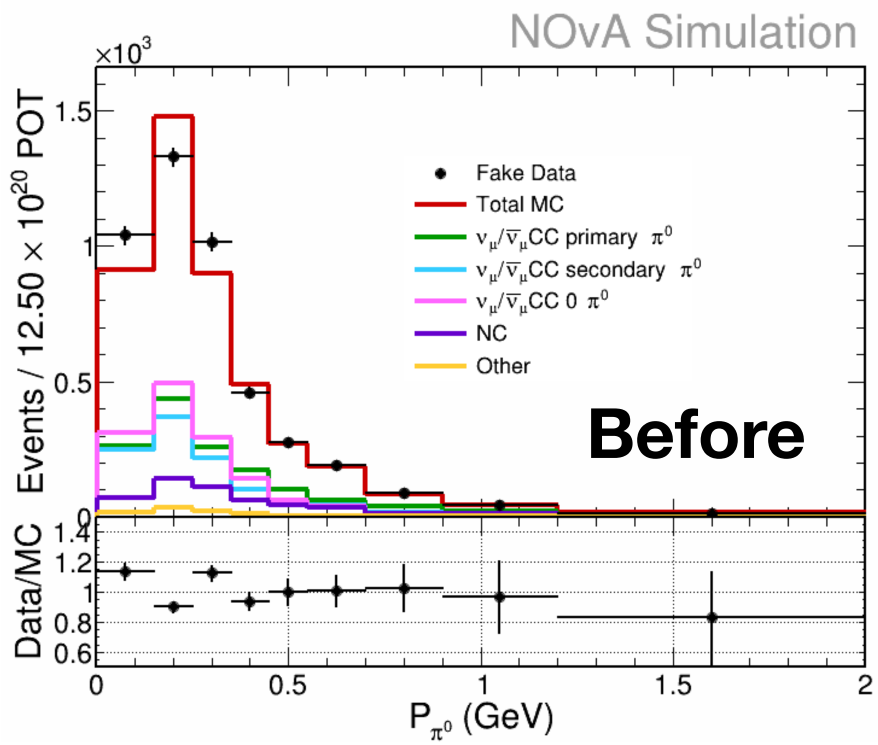
Fake Data Fit Results

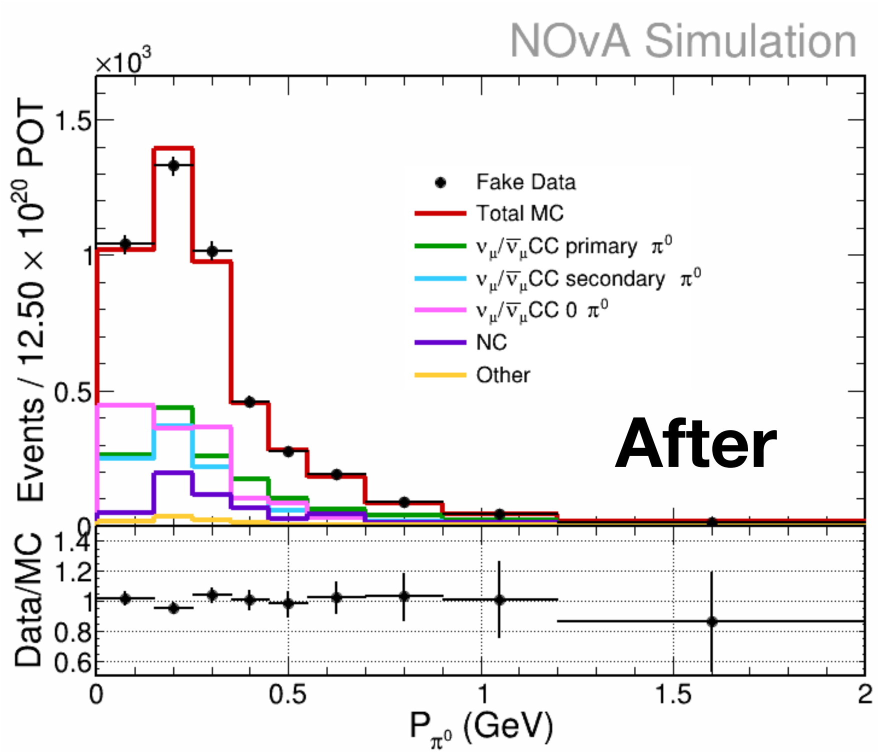
nProngs > 3

Fake Data:

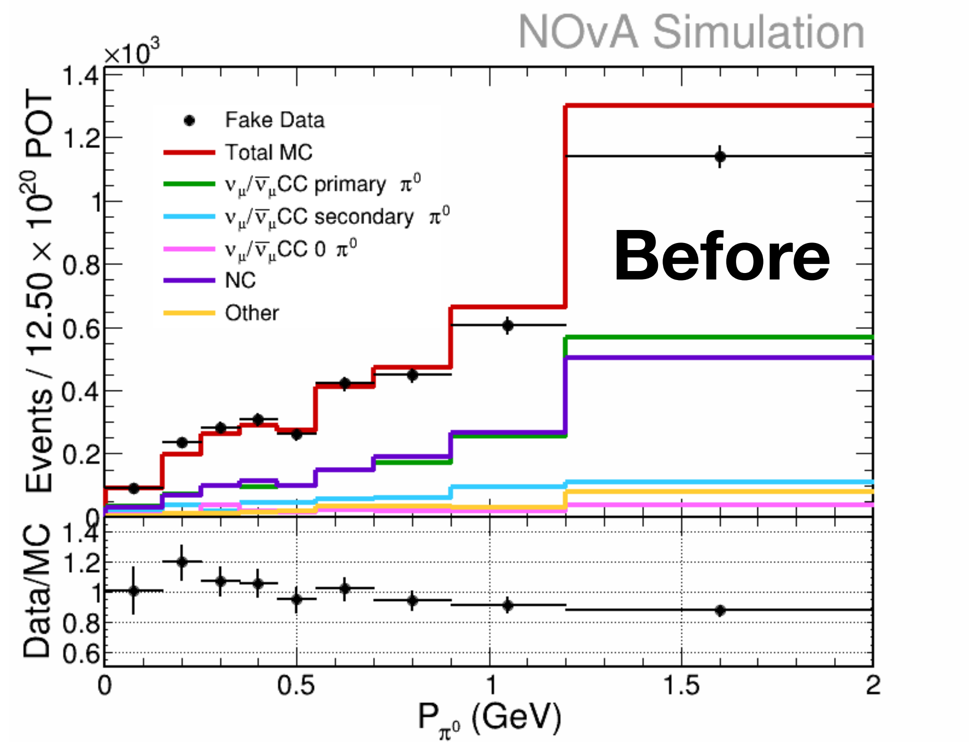
Adjust $\bar{\nu}_\mu/\nu_\mu$CC $0\pi^0$ and **NC** normalizations up or down by 20% in alternating bins

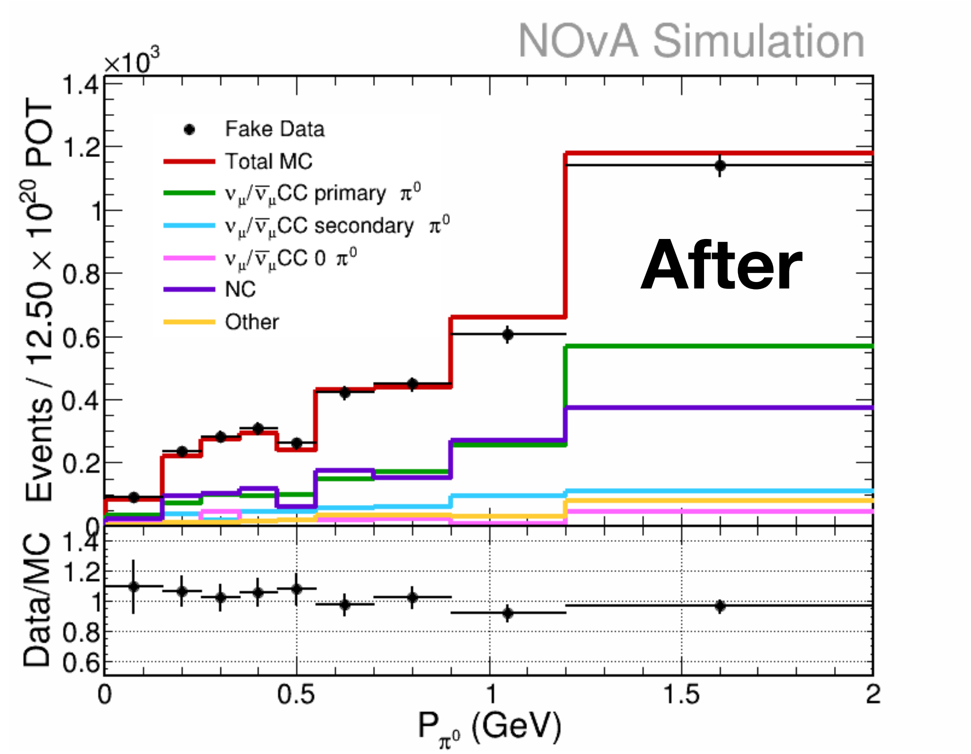
$\bar{\nu}_\mu/\nu_\mu$CC $0\pi^0$ - 1 Sideband





NC Sideband





Fitting χ^2:

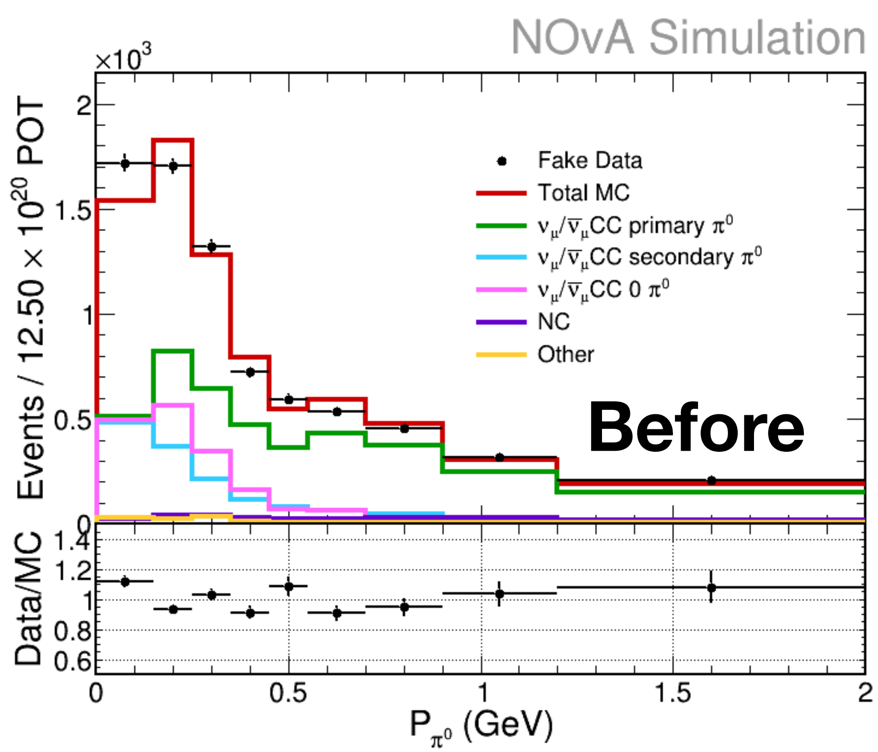
548 (Before)→261 (After)

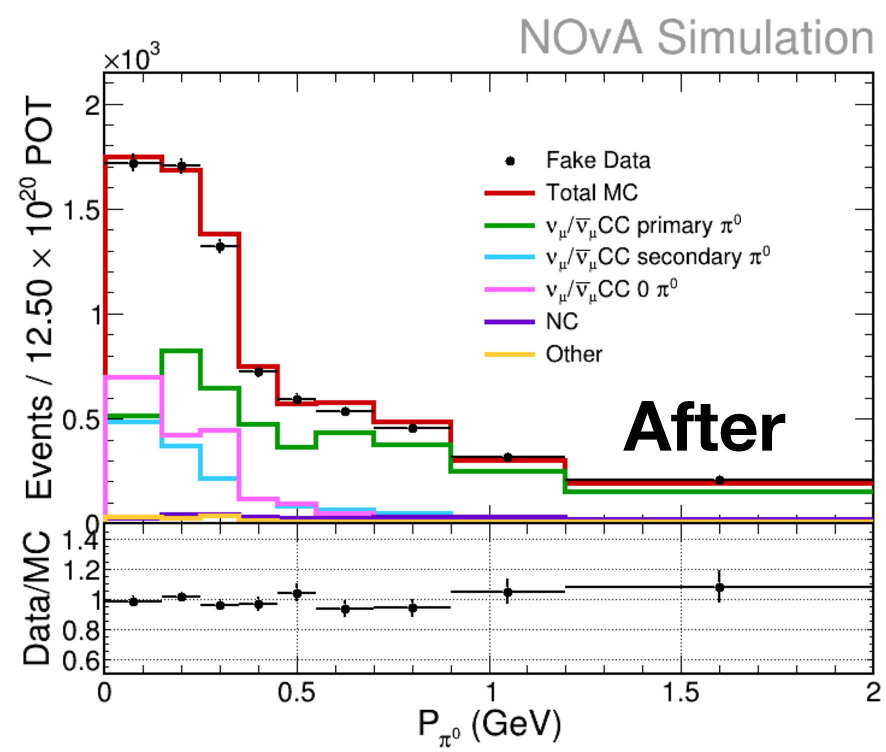
Fake Data Fit Results

- The template fit can be extended to estimate background in **signal region.**

Signal Region

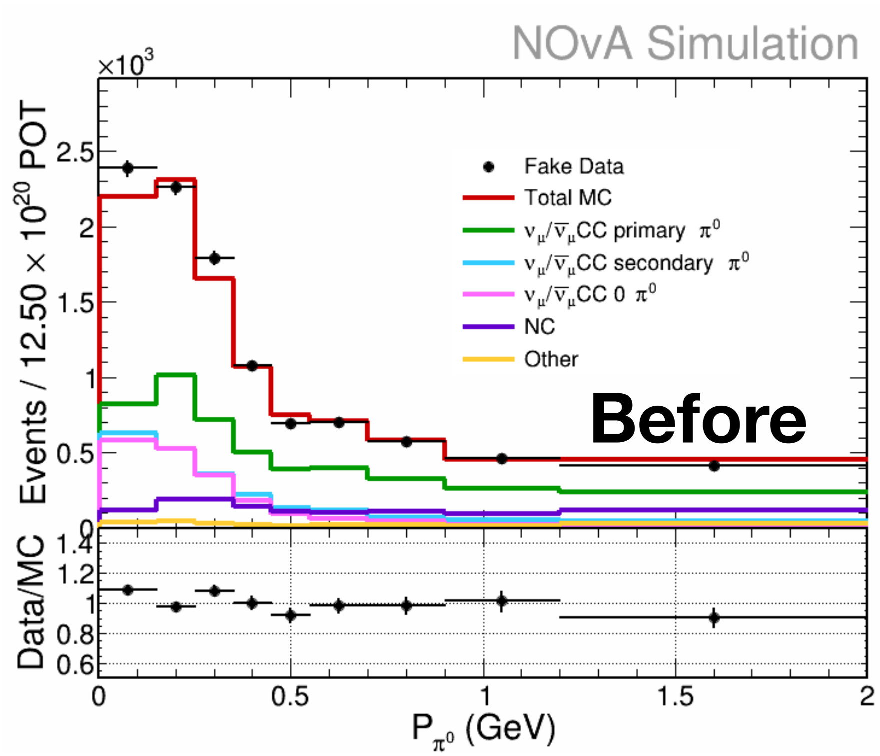
nProngs = 3

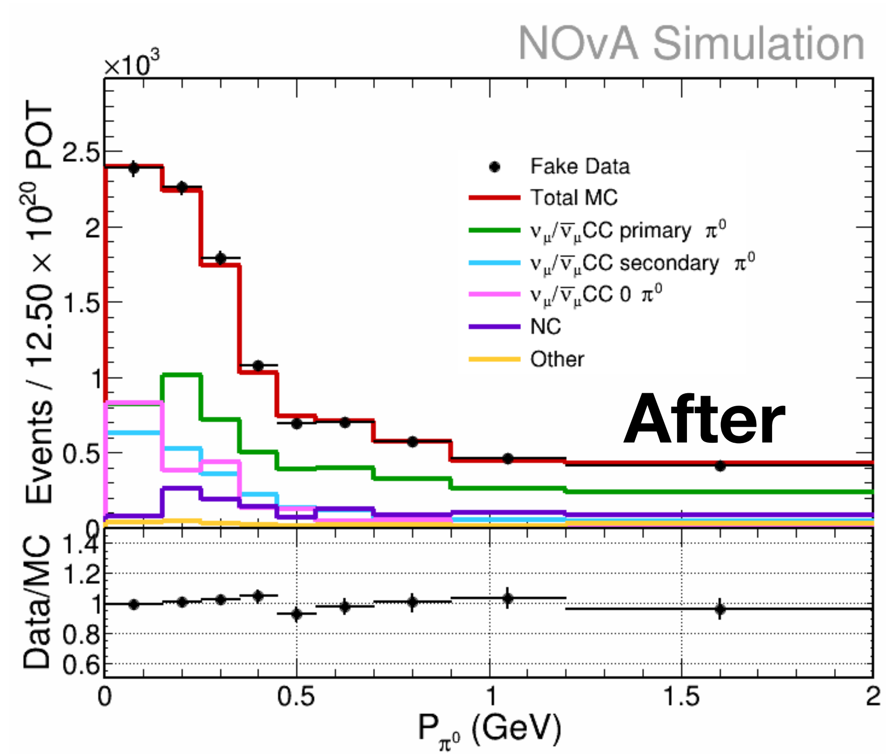




Signal Region

nProngs > 3





Conclusion

- The high statistics antineutrino mode data in the NOvA Near Detector can be used to perform a measurement of the cross section of the $\bar{\nu}_\mu \mathrm{CC}\pi^0$ in the resonance regime.
  - — Differential cross-section measurement with respect to π^0 momentum and angle.
- CNN has been developed for EM shower selection.
  - — Uses single particle prongs for training.
- A data-driven template fit has been developed to estimate $\bar{\nu}_\mu/\nu_\mu \mathrm{CC}\ 0\pi^0$ and NC backgrounds using sidebands.
- Finalizing unfolding and systematic uncertainty estimation.

Expect results soon!

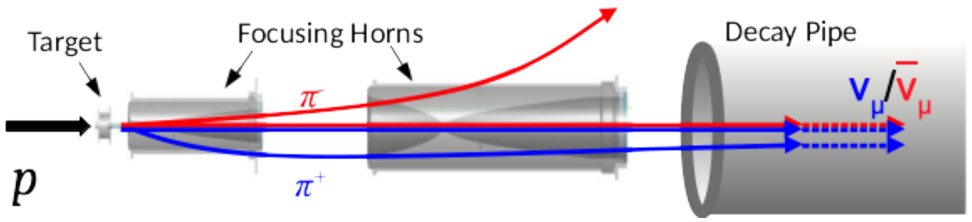
NOvA Collaboration, June 2022 @ Duluth, MN

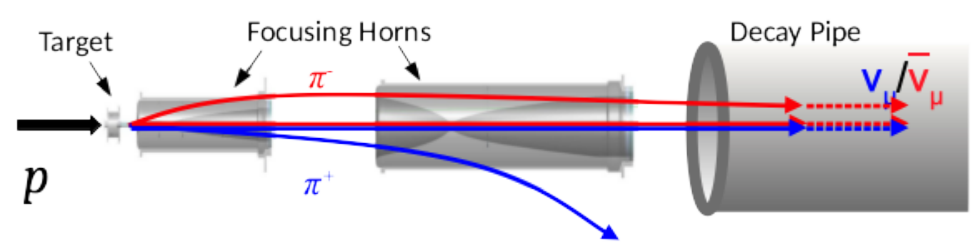
Thank you!

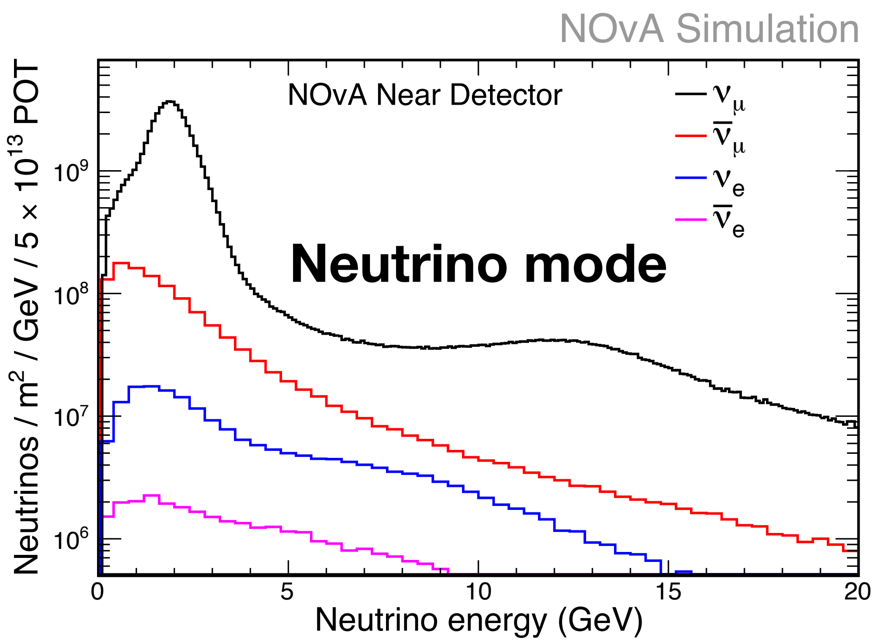
Backup

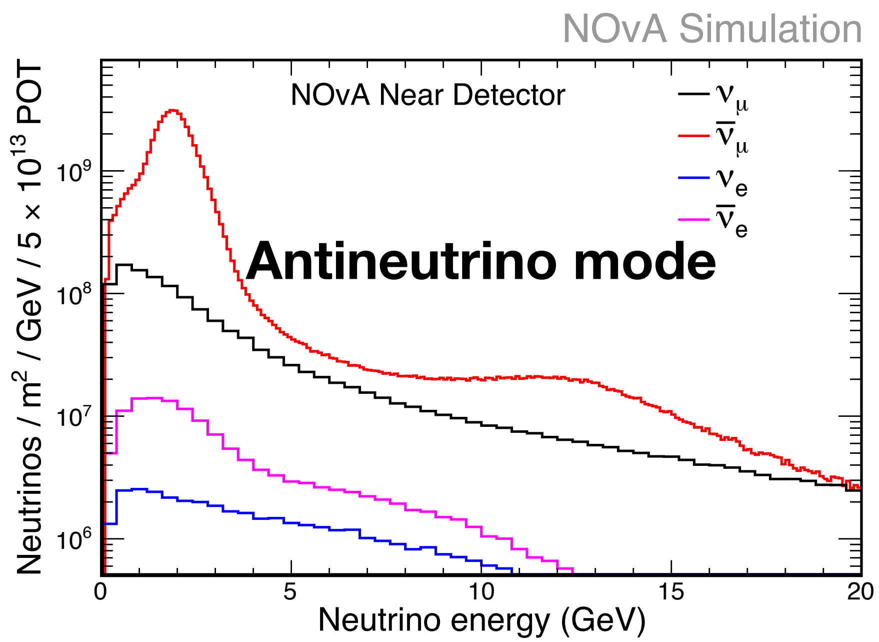
NOvA Flux at Near Detector

- **Forward Horn Current (FHC)** configuration focuses positively charged particles that decay to produce neutrinos.
- **Reverse Horn Current (RHC)** configuration focuses negatively charged particles that decay to produce antineutrinos.





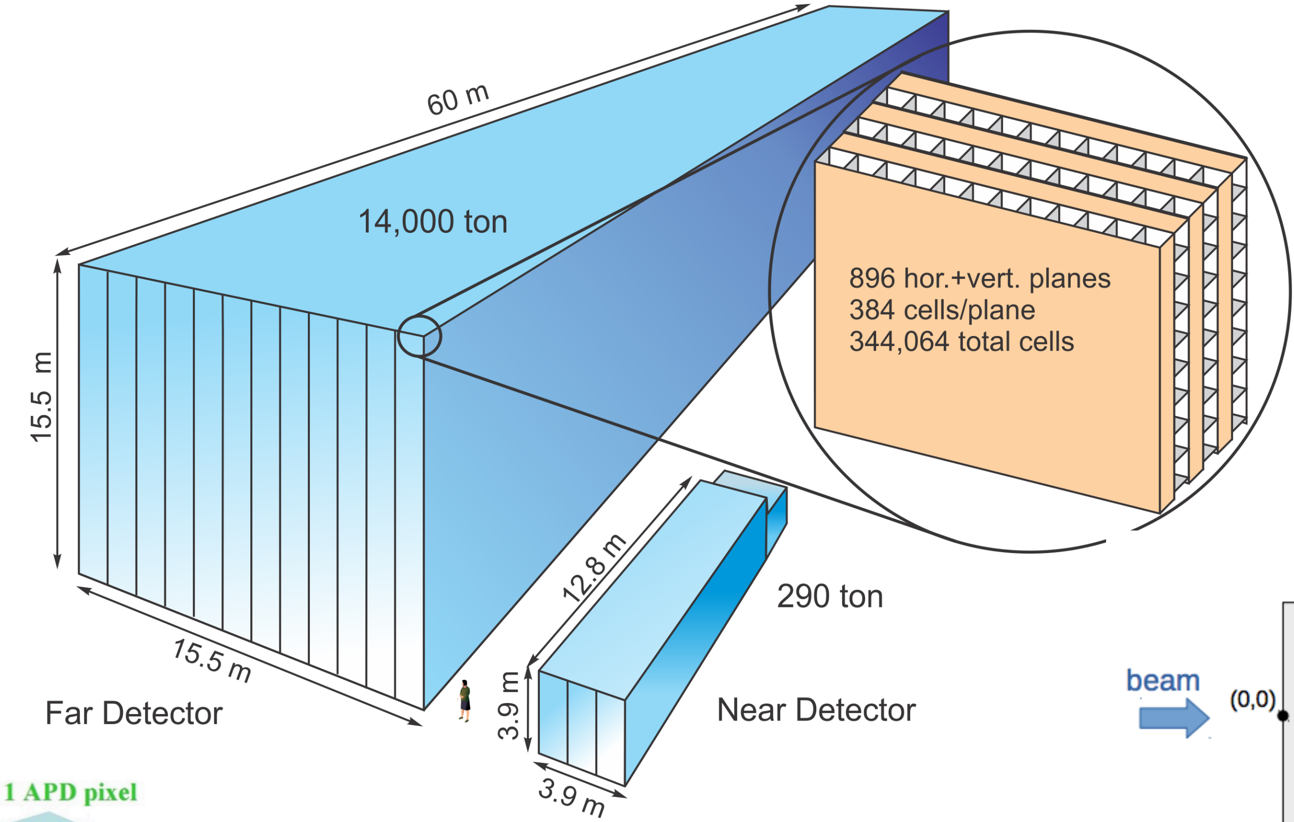




Integrated in [1, 5] GeV neutrino energy,

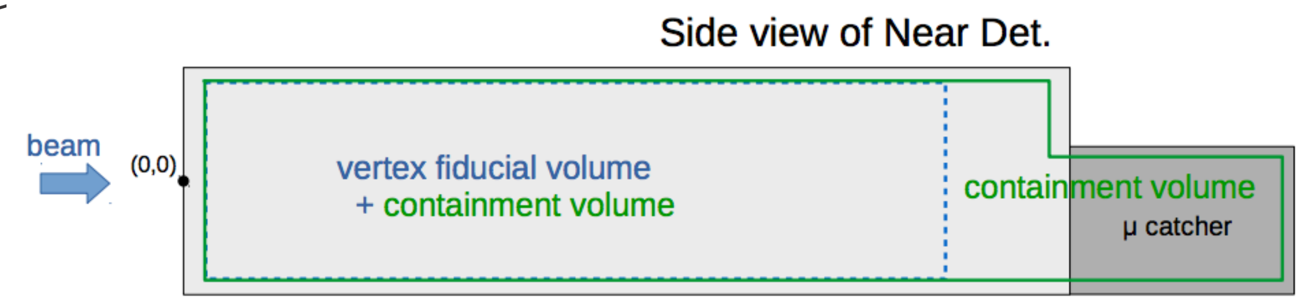
- The FHC beam contains 93.8% ν_μ with 5.3% $\bar{\nu}_\mu$ and 0.9% $\nu_e/\bar{\nu}_e$.
- The RHC beam contains 92.5% $\bar{\nu}_\mu$ with 6.6% ν_μ and 0.9% $\nu_e/\bar{\nu}_e$.

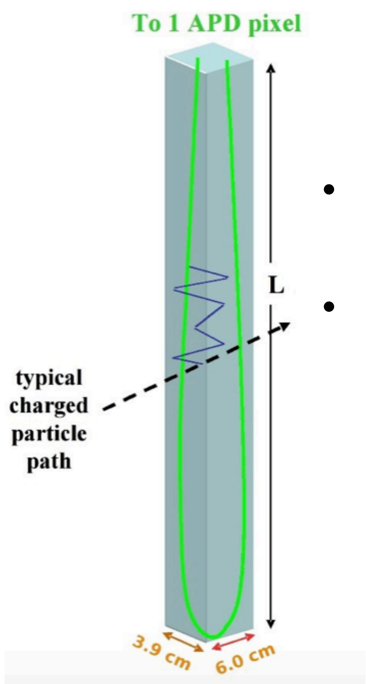
NOvA Detectors



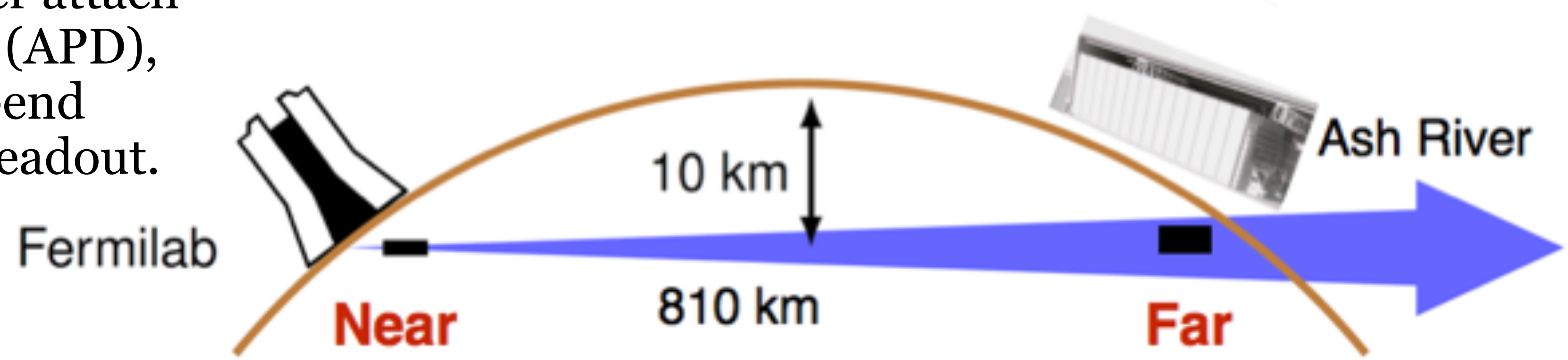
Construction

- PVC plastic cells arranged into planes
- Filled with liquid scintillator
- Horizontal & vertical plane orientations provide a 3D view
- 65% active mass

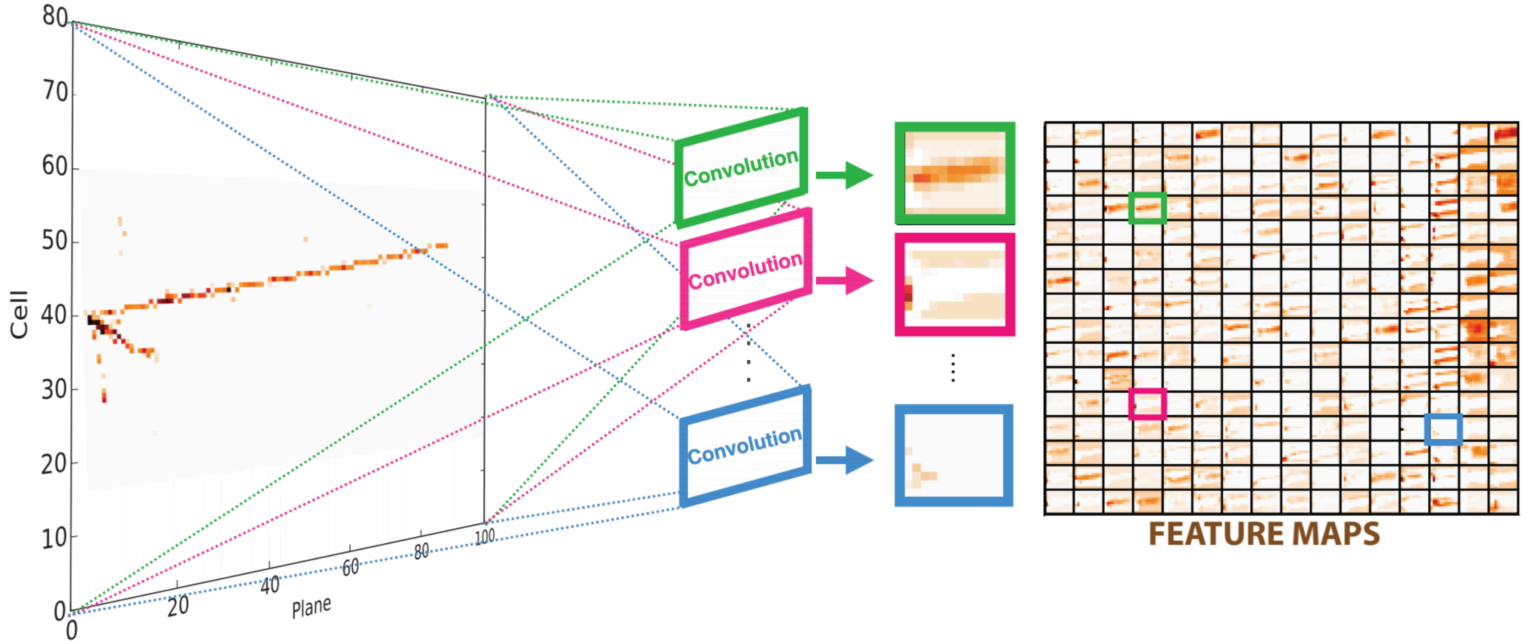




- Each cell has a single wavelength-shifting fiber looped inside it.
- The two free ends of the fiber attach to an avalanche photodiode (APD), which is attached to a front-end board for signal detection/readout.



NOvA Event/Particle Classification



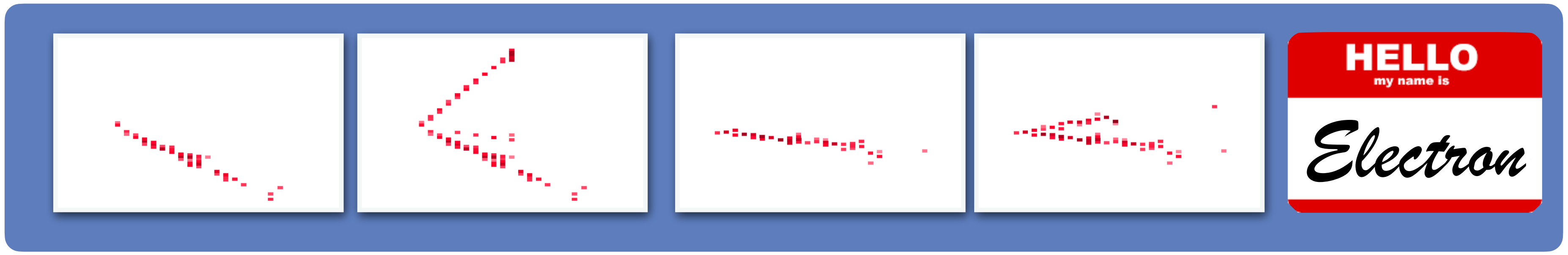
“A Convolutional Neural Network Neutrino Event Classifier”
A. Aurisano, A. Radovic, and D. Rocco *et al*
Journal of Instrumentation, Volume 11, September 2016

Convolutional Neural Network (CNN)
→ Convolutional Visual Network (CVN) in NOvA

- Event Classification:
  Convolutions are applied to **pixel maps** of the events, which are trained to identify particular features (tracks, vertex, showers, etc.). Output of this process is a score by category.
- Particle Identification:
  Identify individual particles within an interaction event, using the full event topology for context.

Addressed Training Bias Issue

- The original Particle-CNN used in oscillation analysis has been trained on both views (XZ-view & YZ-view) of the particle and both views of the entire event, which has bias from neutrino interaction model.



- We had to develop an unbiased training sample for this cross-section measurement.
- Single particle simulation sample was chosen.
  — $e, \gamma, \pi^{\pm}, p, \mu$
  — Uniform distribution in momentum, angle, generated position

Why is this better?

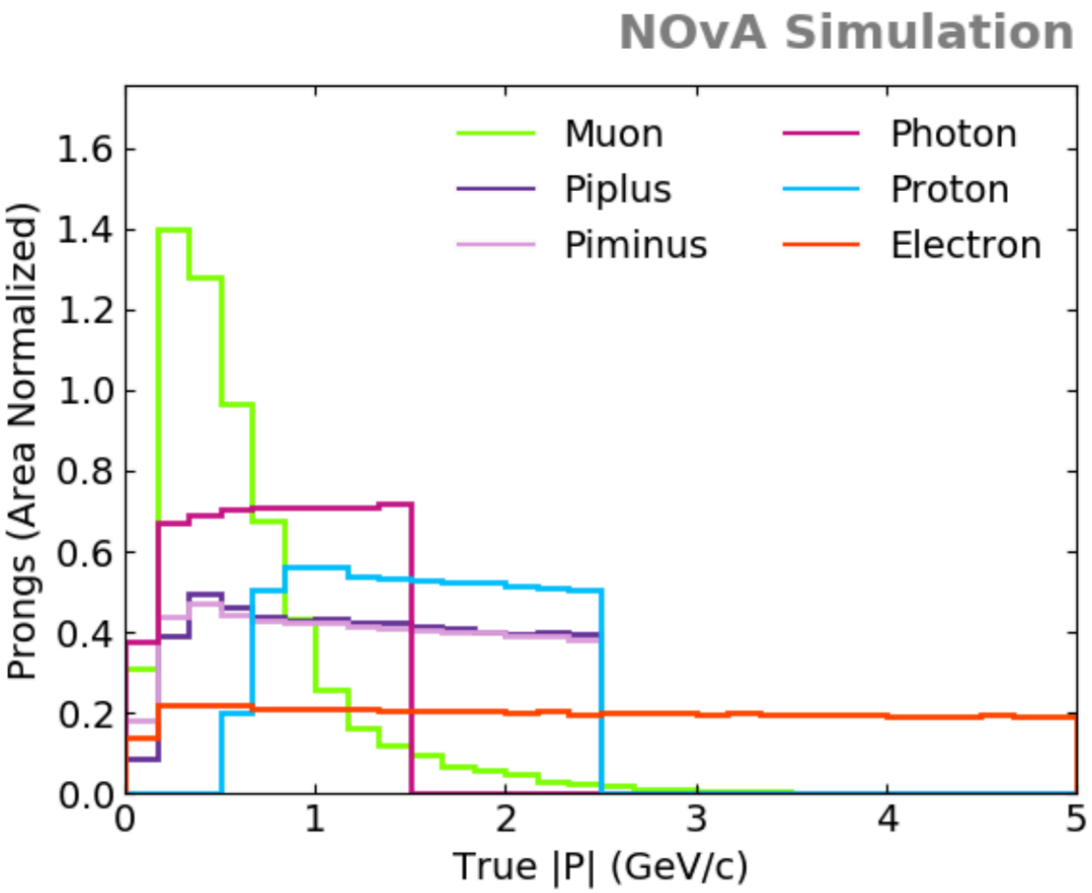
- Neutrino interaction model information is removed from training
- Information about kinematic distribution for final state particles are removed.

NOvA Particle Identification

- Single particle simulation sample was chosen for training.
  - — $e, \gamma, \pi^{\pm}, p, \mu$
  - — Uniform distribution in momentum, angle, generated position

- Binary classification for prongs: Electromagnetic-like (EM-like) vs. non-EM-like
  - — Equal fraction of EM sample and non-EM sample $(\gamma + e)$ vs. $(p + \pi^{\pm})$
  - — μ excluded from training

- **Cuts applied on trained prongs:**
  - — Prong length $\leq$ 500 cm
  - — Prong is produced by generated particles
  - — Most energetic prong
  - — Prong is contained in the detector
  - — Prong quality cut: number of hit ≥ 4



Sample Selection

Preselection
- Slice quality cut
- Fiducial volume cut — Event vertex in fiducial volume
- Tracks/Showers containment cut — All tracks/showers contained, only primary muon track can be in muon catcher
- Muon ID cut

Candidate Events Selection
- 3 or more prongs
  — Muon-like prong: Most collinear with primary muon track
  — Two candidate EM-like prongs: Highest CNN EM scores

Background Reduction Cuts
- Muon kinetic energy cut — $KE_\mu > 0.4$ GeV
- Prong quality cuts — Two candidate EM-like prongs
  Prong 1 $N_{hit} >= 6$, Prong 2 $N_{hit} >= 4$

Sources of Systematic Uncertainties

- Neutrino cross-section systematics
- Particle tracking cross-section systematics
  — Mainly come from $\pi^{\pm} \rightarrow \pi^{0}$ when propagating though the detector
  (the source of secondary π^{0} background)
- Flux modeling systematics
  — Hadron production in the NuMI target (large)
  — Beam transport
- Detector response systematics
  — Simulated light level (large)
  — Absolute calibration
  — Attenuation calibration
- ……